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Fusion Energy Sciences Program at LANL

**Ramon J. Leeper
Program Manager
Fusion Energy Science
Los Alamos National Laboratory
October 17, 2017**

Outline

- **LANL Strategic Plan and Capability Investment Areas**
- **LANL Vision for Existing FES Programs**
- **Leveraging Opportunities in Achieving Our FES Vision**
- **Current LANL FES Portfolio**
- **Summary and Conclusions**

Los Alamos Strategic Plan: Goals leading to action

- Deliver national nuclear security and broader global security solutions

And

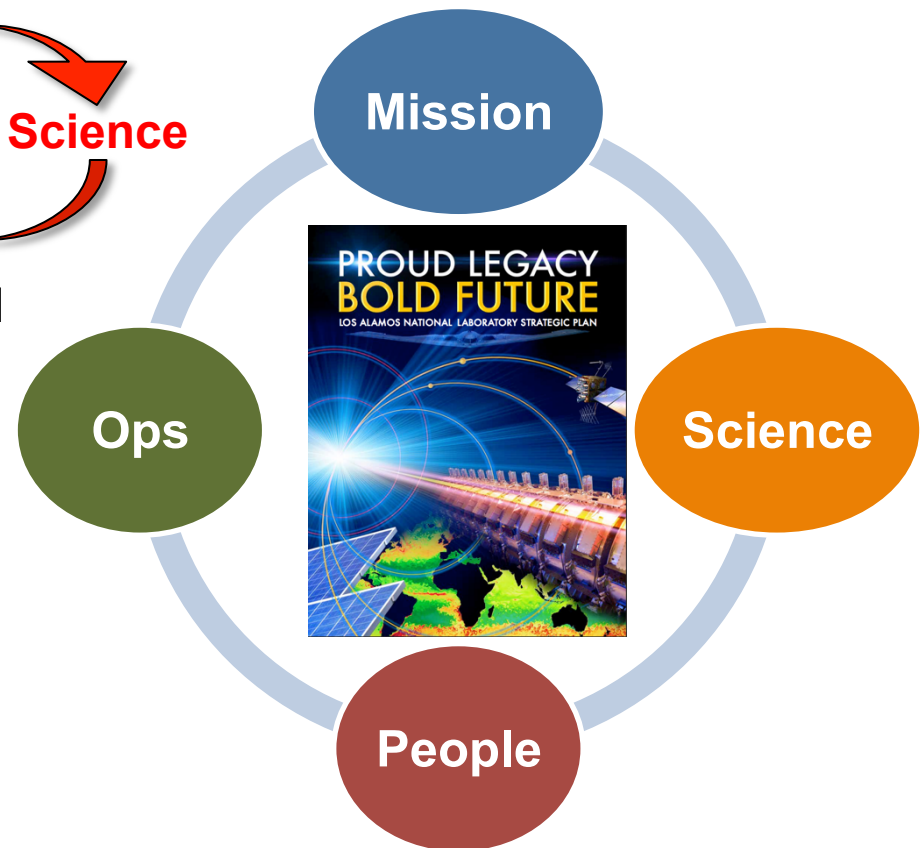
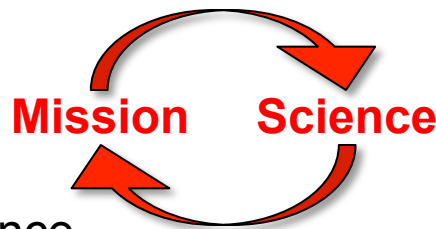
- Foster excellence in science and engineering disciplines essential for national security missions

By

- Attracting, inspiring and developing world-class talent to ensure a vital future workforce

And

- Enabling mission delivery through next-generation facilities, infrastructure, and operational excellence.



We see an enduring future for an integrated Laboratory

— and the need for integrating assets at scale for national security

NUCLEAR WEAPON MISSION

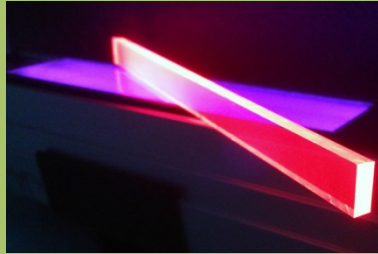


NUCLEAR GLOBAL SECURITY MISSION



Slide 4

Our Science Pillars define strategic capability investment areas at Los Alamos for present and future missions

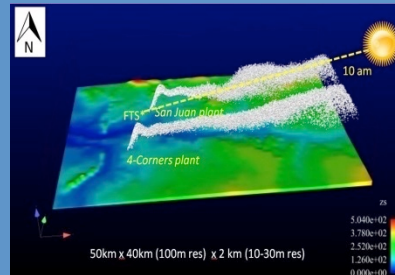


MATERIALS FOR THE FUTURE

Defects and Interfaces

Extreme Environments

Emergent Phenomena

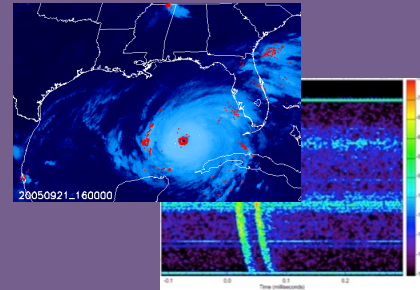


SCIENCE OF SIGNATURES

Discover Signatures

Revolutionize Measurements

Forward Deployment

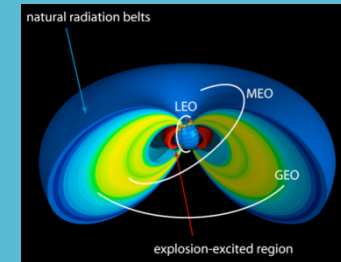


INFORMATION, SCIENCE, AND TECHNOLOGY FOR PREDICTION

Complex Networks

Computational Co-Design

Data Science at Scale



NUCLEAR AND PARTICLE FUTURES

High Energy Density Physics & Fluid Dynamics

Nuclear & Particle Physics, Astrophysics & Cosmology

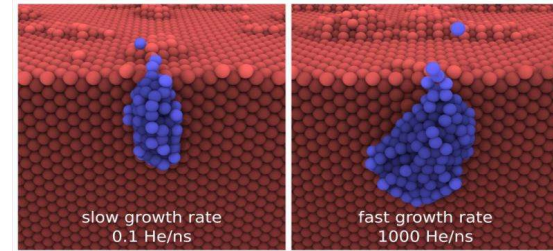
Applied Nuclear Science & Engineering

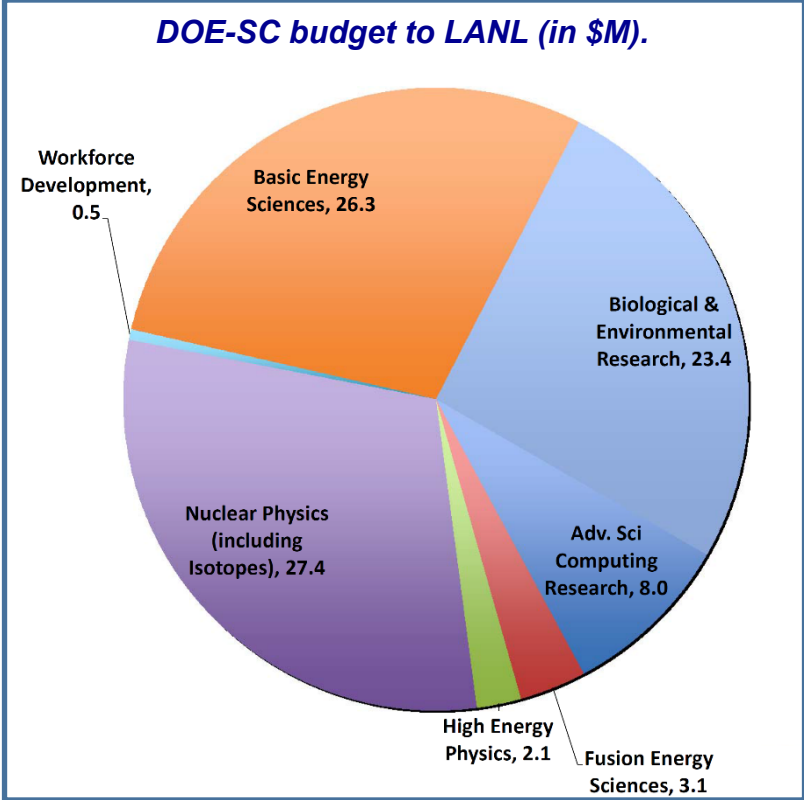

Accelerators & Electrodynamics

LANL FES Vision for Existing Programs

Los Alamos contributes to the National Fusion Energy Sciences Program 10-year strategy, building upon and exercising unique LANL capabilities in magnetic fusion energy and discovery science theory, modeling, simulation, experiments, and technologies. As a DOE multipurpose National Lab, we are in the vanguard of deploying new and novel methodologies, instrumentation, and analyses aligned with the FES Ten-Year Perspective, including tokamak transient control, collaborations on the world-leading stellarator, plasma-material interactions, tritium science, and basic plasma physics discovery.

Leveraging opportunities for achieving our FES vision as a multipurpose National Lab



- **Leveraging our NNSA National Security Program**
 - **Science Program**, e.g., materials science on the LCLS MEC Station; imaging techniques applied to US ITER disruption mitigation; DARHT & ICF diagnostics applied that can lead to world-class runaway electron measurements.
 - **High-Performance Computing**, e.g., SC-NNSA Exascale Computing Project; \$10 M/year for Institutional computing.
 - **LDRD program** (~\$120M/yr) strategic investments to demonstrate untested concepts, extend physics reach, and integrate theory and experiment (Directed Research: ~\$1.6M/yr; Exploratory Research: ~\$150K - \$400K/yr)
 - **M&O Contract Fee**, e.g., U.California investments to UCSD PISCES-LANL Ion Beam Materials Lab collaboration.
- **Leveraging our DOE Office of Science Programs:** 

| Program | Budget (\$M) |
|--------------------------------------|--------------|
| Basic Energy Sciences | 26.3 |
| Biological & Environmental Research | 23.4 |
| Nuclear Physics (including Isotopes) | 27.4 |
| Adv. Sci Computing Research | 8.0 |
| Fusion Energy Sciences | 3.1 |
| High Energy Physics | 2.1 |
| Workforce Development | 0.5 |

 - **ASCR**: Applied Math Programs (e.g., Chacon); Computer Science (Exascale Computing Project); and SciDAC (e.g., Tang, Voter, & Uberuaga).
 - **BES**: Accelerated molecular dynamic simulations; understanding and developing materials in extreme radiation environments; National Scientific User Facility Center for Integrated Nanotechnologies (CINT); Energy Frontier Research Center for Advanced Solar Photophysics (CASP).
- **Leveraging our Applied Energy and ARPA-E Programs:** e.g., radiation damage experiments on LANSCE and Paul Scherrer Inst and post irradiation evaluation; NE Consortium for the Advanced Simulation of Light Water Reactors (CASL) Hub; ARPA-E (Imploding Plasma Liners).

LANL FES Priorities

Burning Plasma Foundations & Long Pulse

- **Magnetic Fusion Theory & Modeling**
- **Runaway Electron Research**
- **LANL W7-X Physics and Diagnostics**
- **NSTX-U Collaboration**
- **EAST Tokamak Collaboration**

Tritium Science Research

Discovery Plasma Science

- **High-Fidelity Kinetic Modeling of Magnetic Reconnection in Laboratory Experiments**
- **Fundamental Plasma-Shock Physics**

Burning Plasma Foundations & Long Pulse

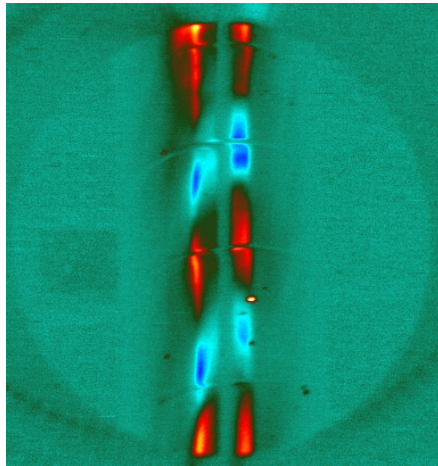
Magnetic Fusion Theory & Modeling

- **LANL's fusion theory program develops physics basis and predictive simulation for (1) plasma particle/power exhaust solutions for tokamak reactors; and (2) transport physics for tokamak disruption mitigation.**
 - Sheath theory/modeling and particle/power recycling for plasma materials interaction.
 - Transport in stochastic and open field line plasmas, including runaways.
 - Interaction between micro-turbulence and macro-stability via plasma currents.
- **Highlights from recent research:**
 - A new theory that reveals the essential role of electron heat flux in setting the Bohm speed in the Bohm criterion for a warm-ion plasma [PoP Letters 23, 120701 (2016)]
 - A kinetic sheath model for the collisionless sheath of a collisional plasma that agrees with first-principles kinetic simulations [PoP 23, 083503 (2016)]
 - A theory that connects plasma power recycling to the boundary plasma density and temperature for reactor plasma in detached and attached regimes [Fusion Science & Technology 71, 110-121 (2017)]
 - Impact of the improved sheath boundary condition and power recycling characteristics on scrape-off layer plasma modeling [Fusion Science & Technology 71, 103 (2017)]
 - A comprehensive theory on the various mechanisms by which the microturbulence affects macroscopic plasma current and hence global stability (PoP, submitted).
 - Analytical and semi-analytical models of the runaway electron distribution in the runaway vortex regime (PoP, submitted).
 - Theoretical model for the modified Coulomb algorithm in the hybrid small-angle and large collisions for runaway avalanche studies (PoP, submitted)

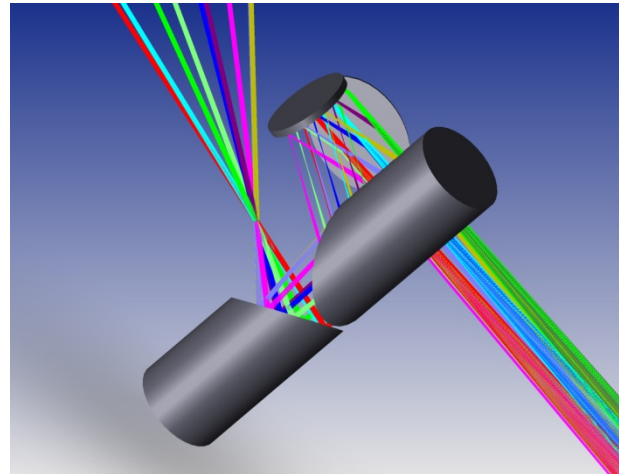
Runaway Electron Research

- **LANL focus: develop relativistic electron Fokker-Planck solvers in toroidal geometry and apply them to uncover the fundamental physics underlying the saturation of runaway electrons in a tokamak.**
- **Key physics accomplishments (excellent examples of learning fundamental physics through large-scale simulation):**
 - **Establish the fundamental role of so-called runaway vortex in the saturation of primary runaway electron distribution, particularly the location of the runaway bump and its energy and pitch angle spread. Build reduced model for accurate predictions. [PPCF 59, 044003 (2017)]**
 - **Establish a first-principle computational modeling capability for runaway avalanche, properly taking into account the large-angle collisions. Elucidate that runaway avalanche threshold is governed by O-X merger of the primary runaway vortex. Build a reduced model that accurately predicts the avalanche threshold. [PRL, to be submitted]**

LANL W7-X Physics and Diagnostics



Fast transient IR fluctuations were seen on a limiter during first plasma



Two off-axis parabolic mirrors combined with two flat turning mirrors will enable a pinhole view of the Scraper Element. IR/visible system is in final design, for construction and installation by Jan. 2018

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Nucl. Fusion 57 (2017) 056036 (11pp)

Nuclear Fusion

<https://doi.org/10.1088/1741-4326/aa6609>

Limiter observations during W7-X first plasmas

G.A. Wurden¹, C. Biedermann², F. Effenberg³, M. Jakubowski^{1,4}, H. Niemann⁵, L. Stephey¹, S. Bozhakov⁶, S. Brezinsek⁷, J. Fellinger², B. Cannas⁶, F. Pisano⁶, S. Marsen⁷, H.P. Laqua⁶, R. König⁶, O. Schmitz⁷, J.H. Harris⁷, E.A. Unterberg⁷ and the W7-X Team⁷

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Abstract

During the first operational phase (referred to as OP1.1) of the new Wendelstein 7-X (W7-X) stellarator, five poloidal graphite limiters were mounted on the inboard side of the vacuum vessel, one in each of the five toroidal modules which form the W7-X vacuum vessel. Each limiter consisted of nine specially shaped graphite tiles, designed to conform to the last closed field line geometry in the bean-shaped section of the standard OP1.1 magnetic field configuration (Sonn Pedersen et al 2015 *Nucl. Fusion* 55 126001). We observed the limiters with multiple infrared

Recent Publications

- 1). G. A. Wurden, et al, "Limiter Observations during W7-X first plasmas", *Nuclear Fusion*, 57(5) 056036 (2017) <https://doi.org/10.1088/1741-4326/aa6609>
- 2). S. A. Lazerson, M. Otte, et al, "Error field measurement, correction and heat flux balancing on Wendelstein 7-X", *Nuclear Fusion*, 57, 046026 (2017) <http://iopscience.iop.org/article/10.1088/1741-4326/aa60e7/meta>
- 3). T. S. Pederson, M. Otte, et al, "Confirmation of the topology of the Wendelstein 7-X magnetic field to better than 1:100,000", *Nature Communications*, 7, 13493 (2016) <https://www.nature.com/articles/ncomms13493>

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ENERGY

Office of
Science



Slide 12

EAST tokamak Collaboration



Scientific Achievement

A new class of structured pellets called core-shell pellets have been proposed and are being investigated for EAST and other magnetic fusion devices. Attractive features such as precise material release have been recognized, it's potential applications for *impurity transport* and *ELM physics* have been described and proposed for the upcoming EAST experiments.

Significance and Impact

Controlling the intense heat and particle fluxes expected in ITER and future magnetic fusion reactors poses prohibitive problems to the design, selection and maintenance of the first wall and divertor materials. Some innovative solutions to the material challenges may come from mass injection of different sizes, frequencies and materials composition. In addition to diagnostic applications, controlled injection of micropellets of different sizes and velocities at different frequencies will offer several possibilities: a.) Better assessment of the core plasma cooling due to dust produced in-situ; b.) Better understanding of the plasma-material interaction physics near the wall; c.) New methods for plasma fueling and impurity control; and d.) Reliable techniques that can achieve edge cooling without compromising the plasma core.

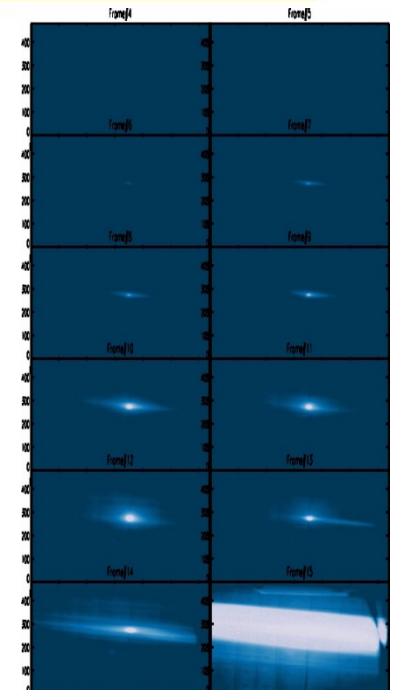
Research Details

Semi-analytical models for pellet-plasma interactions.

Fabrication methods for core-shell pellets.



Core-shell spheres



EAST pellet ablation

Z. Sun, et al., 'ELM Control by Lithium Aerosol and Granule Injection on EAST with Tungsten Divertor,' in preparation (2017); J. Hu, et al., 'Summary of upgrade and experiments of lithium systems on EAST tokamak in the last two years.' in preparation (2017);

Tritium Science

Tritium Science Research

| | | FY16 (\$K) | FY17 (\$K) |
|--|--------------------------------------|---------------|---------------|
| Tritium Processing Development for Magnetic Fusion | Hydrogen Processing Laboratory (HPL) | 285 | 285 |
| | TSTA Data Mining Project | 185 | 65 |

- The HPL is a pilot scale gas handling system that can be used for experimental, design and validation studies for tritium processing. The benefit of the HPL is that by using hydrogen instead of tritium the safety design and overhead cost associated radioactive processing can be reduced by using the hydrogen isotope as a surrogate for tritium.
- The Tritium System Test Assembly (TSTA) was a state of the art facility at LANL that operated from 1980-2000. During this time many reports and publications were released in support of FES. Approximately 31,163 (± 9000) typed pages and 4044 hand-written notebook pages have been scanned. The files were converted to a searchable form using an Optical Character Recognition (OCR) software. The database is available to the tritium community for historical data and experience upon request.



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Current / Future Research Details (FY17/18)

- Complete expanded upgrades to HPL data acquisition and control system and testing of PMR for comparison with previous reported data for ITER TEP design
- Transfer TSTA Database to open server for tritium community
- Expanded work into Liquid Metal Plasma Facing Component (LM/PFC) Working Group

Recent Presentations

- W. Kirk Hollis, et al., *Export Control Requirements for Tritium Processing Design and R&D*, LA-UR-15-28493 Version 2

Discovery Plasma Science

High-fidelity kinetic modeling of magnetic reconnection in Lab experiments

Scientific Achievement

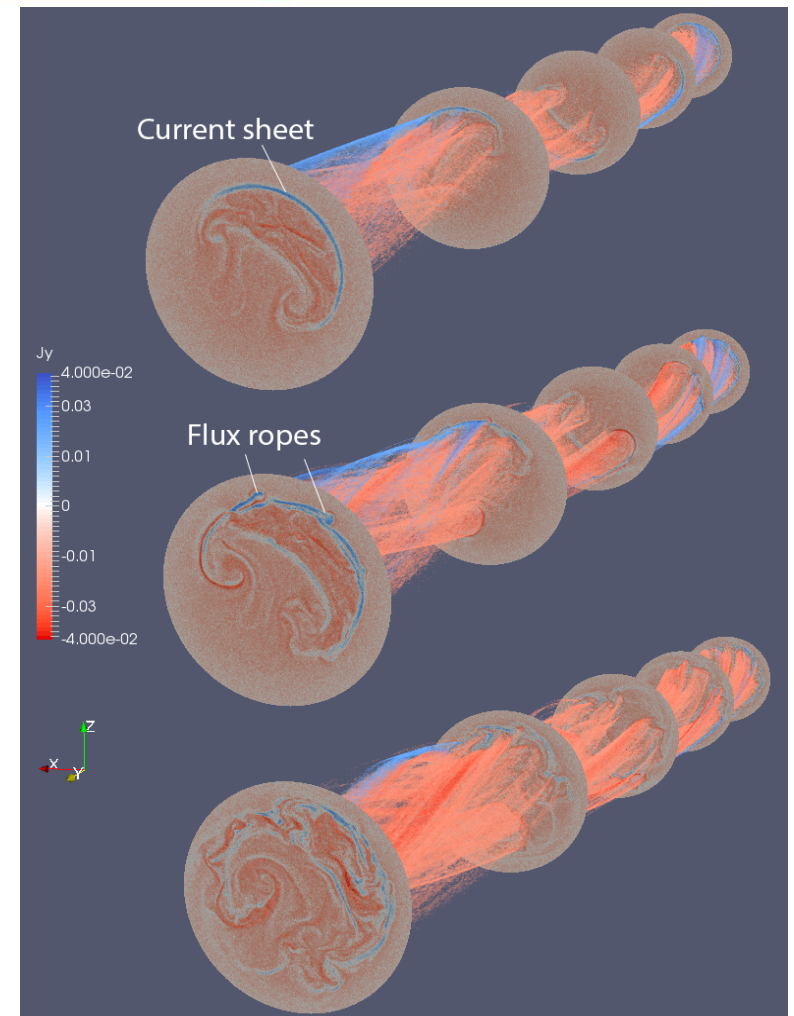
We are extending the fully kinetic VPIC code to cylindrical geometry, permitting experimental boundary conditions, drive coils, and Coulomb collisions. Code is optimized to take advantage of new KNL architecture.

Significance and Impact

The new code will be used to model laboratory reconnection experiments (FLARE – Princeton Plasma Physics Laboratory, T-REX – University of Wisconsin, Madison). The code will also be used to study fusion relevant regimes, and is open-source to permit broad collaborations for users of these facilities.

Research Details

Preliminary simulation showing nonlinear evolution of internal kink instability, which drives formation of current sheet. As magnetic reconnection develops, this helical current sheet (blue) breaks-up due to the collisionless plasmoid instability.



Stanier et al, in preparation, 2017

Fundamental Plasma-Shock Physics

Scientific Achievement

Merging, supersonic plasma jets are being used to generate and study the fundamental physics of plasma shocks. In Year 1 (FY17) of this project, we are focused on characterizing the shock structure and dynamics of a collisional plasma shock, and comparing the results with two-fluid plasma theory and hybrid-PIC simulations.

Significance and Impact

Shocks are an elementary process in plasmas, ubiquitous in space, astrophysical, and high-energy-density plasmas. Plasma shocks differ in fundamental ways from hydrodynamic shocks. Our best computer codes are not yet fully predictive for plasma shocks, especially in the presence of complex equation of state (EOS). A validated predictive capability would be of great interest/benefit for a wide range of plasma, astrophysics, and fusion-related research.

Research Details

Detailed diagnostic data of a collisional plasma shock, including fast gated CCD images (Fig. 1), spectroscopy (Fig. 2), and interferometry (not shown) are being used for first-of-a-kind measurements relating to collisional plasma shocks in a laboratory plasma. Planned additional diagnostics for this project include electrostatic/magnetic probes and ion energy analyzers.



Operated by Los Alamos National Security, LLC for NNSA



Fig. 1. FY17 research: three argon plasma jets launched by coaxial plasma guns (developed for ARPA-E-sponsored research) merge at an oblique angle, forming collisional plasma shocks between adjacent jets. We are now making detailed diagnostic measurements of the shock structure and dynamics.

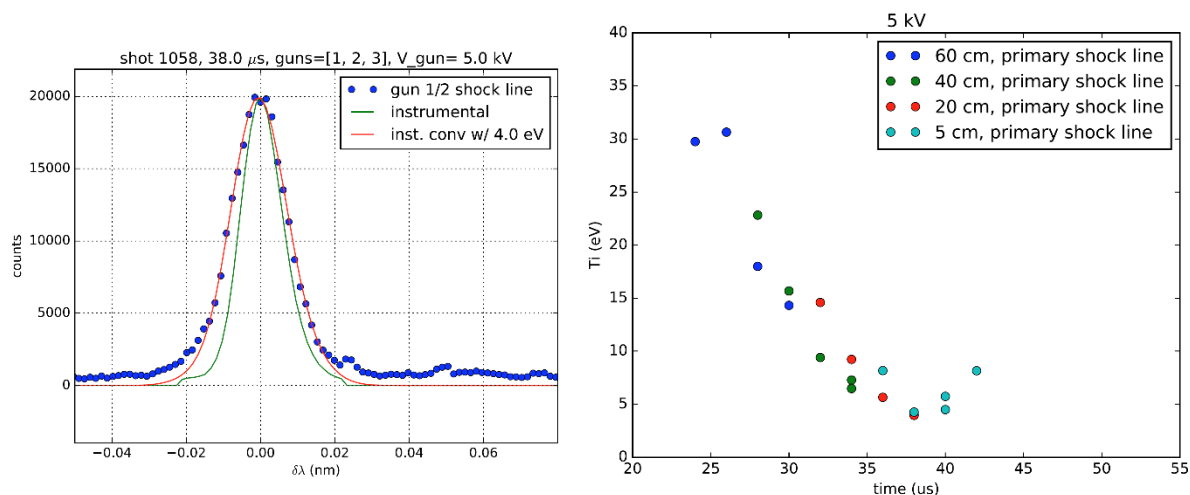


Fig. 2. FY17 research: (left) Example of chord-averaged Doppler-broadened line emission from singly ionized argon, from which we infer ion temperature T_i at a plasma shock. (b) T_i vs. time at various positions from target-chamber center, showing initially high T_i upon shock formation and then rapid cooling of ions over time. These are the first direct, localized measurements of T_i , to our knowledge, in a laboratory collisional plasma shock.

UNCLASSIFIED

Research supported by the DOE Office of Fusion Energy Sciences, leveraging ARPA-E support (through FY18) of PLX facility operation and hardware maintenance/upgrades.

Slide 19



Summary and Conclusions

- **LANL core theory, modeling, and simulation program, while relatively small, remains strong and impactful**
- **Thanks to recent budget increments from FES, LANL is achieving higher-impact contributions to the U.S. W7-X collaboration**
- **LANL theory, simulation, and experimental achievements in discovery plasma science have been significant**
- **LANL contributions to FES continues to benefit from significant leverage from our NNSA, LDRD, BES, ASCR, Applied Energy, and ARPA-E programs**
- **With a relatively low budget, we make significant contributions to FES programs**

Backup Slides

2016 LANL Publications: Burning Plasmas Foundations & Long Pulse

Lumsdaine, A., et al., (LANL author: **G. A. Wurden**) 2016: Overview of Design and Analysis Activities for the W7-X Scraper Element. *IEEE Transactions on Plasma Science*, **44**, 1739-1744.

<https://doi.org/10.1109/TPS.2016.2598486>

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Plaud-Ramos, K. O., M. S. Freeman, W. Wei, E. Guardincerri, J. D. Bacon, J. Cowan, J. M. Durham, D. Huang, J. Gao, M.A. Hoffbauer, D. J. Morley, C. L. Morris, D. C. Poulson, and Z. Wang, 2016: A study of CR-39 plastic charged-particle detector replacement by consuming imaging sensors. *Rev. Sci. Instrum.*, **87**, 11E706. <http://dx.doi.org/10.1063/1.4960168>

Tang, X.-Z., and Z. Guo, 2016: Kinetic model for the collisionless sheath of a collisional plasma. *Phys Plasmas*, **23**, 083503. <http://dx.doi.org/10.1063/1.4960321>

Tang, X.-Z., and Z. Guo, 2016: Critical role of electron heat flux on Bohm criterion. *Phys. Plasmas*, **23**, 120701. <http://dx.doi.org/10.1063/1.4971808>

2017 (YTD) LANL Publications: Burning Plasmas Foundations & Long Pulse

Canik, J. M., and **X.-Z. Tang**, 2017: Sensitivity of the Boundary Plasma to the Plasma-Material Interface. *Fusion Sci. Technol.*, **71**, 103-109. <http://dx.doi.org/10.13182/FST16-124>

Guo, Z., **C. J. McDevitt**, and **X-Z. Tang**, 2017: Phase-space dynamics of runaway electrons in magnetic fields. *Plasma Phys. Control. Fusion*, **59**, 044003. <https://doi.org/10.1088/1361-6587/aa5952> (SciDAC FES/ASCR)

Lazerson, S. A., et. al., (LANL author: **G. A. Wurden**) 2017: Error field measurement, correction and heat flux balancing on Wendelstein 7-X. *Nuclear Fusion*, **57**, 046026. <http://iopscience.iop.org/article/10.1088/1741-4326/aa60e7/meta>

Tang, X-Z., and **Z. Guo**, 2017: Plasma Power Recycling at the Divertor Surface. *Fusion Sci. Technol.*, **71**, 110-121. <http://dx.doi.org/10.13182/FST16-119>

Wurden, G. A., et al., 2017: Limiter Observations during W7-X first plasmas. *Nuclear Fusion*, **57**, 056036. <https://doi.org/10.1088/1741-4326/aa6609>

2016 LANL Publications: Discovery Plasma Science (p. 1)

- Akçay, C., W. Daughton, V. S. Lukin, and Y.-H. Liu, 2016: A two-fluid study of oblique tearing modes in a force – free current sheet. *Phys. Plasmas*, **23**, 012112. <http://dx.doi.org/10.1063/1.4940945>
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2016 LANL Publications: Discovery Plasma Science (p. 2)

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- Guo, F.**, et al., (LANL authors: **X. Li, H. Li, W. Daughton, N. Lloyd-Ronning, H. Zhang**) 2016: Efficient production of high-energy nonthermal particles during magnetic reconnection in a magnetically dominated ion-electron plasma. *Astrophys. J. Lett.*, **818**, L9. <http://dx.doi.org/10.3847/2041-8205/818/1/L9>
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- Jin, S., **S. Li**, A. Isella, **H. Li**, and J. Ji, 2016: Modeling Dust Emission of HL Tau Disk Based on Planet-Disk Interactions. *Astrophys. J.*, **818**, 76. <http://dx.doi.org/10.3847/0004-637X/818/1/76>
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- Hao, Y., B. Lembege, Q. Lu, and **F. Guo**, 2016: Formation of downstream high speed jets by a rippled nonstationary quasi-parallel shock: 2-D hybrid simulations”, *J. Geophys. Res.*, **121**, 2080-2094. <https://doi.org/10.1002/2015JA02419>
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Stability of Relativistic Astrophysical Jets and the Associated Particle Acceleration (Li): Highlights

Scientific Achievement

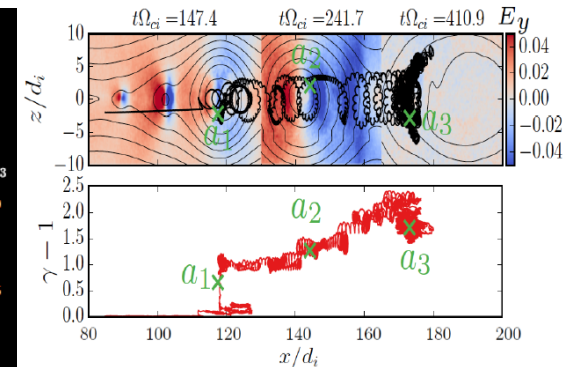
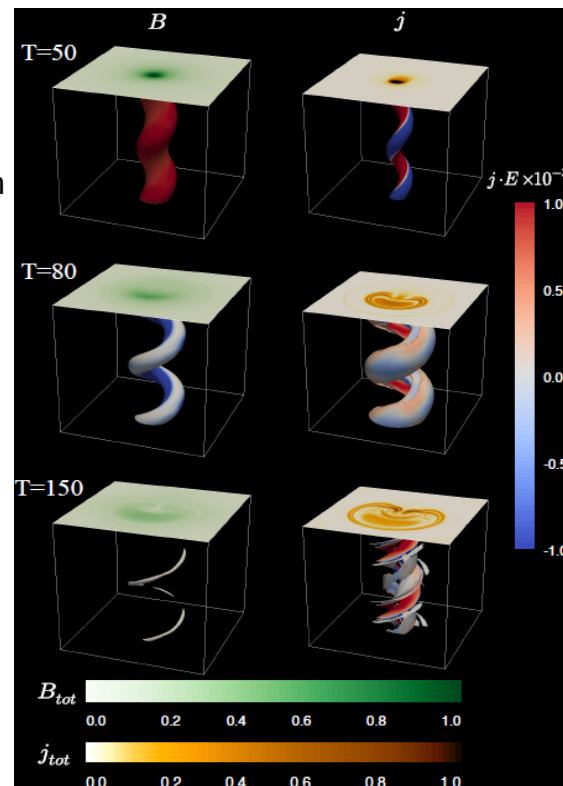
Through extensive relativistic MHD and PIC studies of astrophysical jets along with their instabilities and the associated particle acceleration, we found that kink instability can lead to flares from such sources and significant non-thermal particle distributions can be produced, which is related to a Fermi-like acceleration process by curvature drifts.

Significance and Impact

These simulations were the first in relating global jet (in)stability with kinetic dissipation and radiative signatures. These results have been applied to observations of jets from black holes and gamma-ray bursts.

Research Details

Large-scale 2D/3D MHD and PIC simulations were performed using LANL developed codes. Detailed analyses show global instability initiated dissipation can produce distinct signatures in polari:



(left) 3D isosurface of $|B|$ (left) and $|J|$ (right), showing the evolution of kink instability along with the associated magnetic energy dissipation in a relativistic jet.

(top) Individual particle dynamics and energization in a low-beta plasma reconnection. A series of plasmoids are produced which scatter particles efficiently during the acceleration process.

Work supported by DoE FES

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